

Upper Bound on the Energy of Particles and Their Secondary Neutrinos

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We derive an upper limit to the energy of nuclei accelerated via the Fermi mechanism in any relativistic shockwave, driven by any astrophysical engine. This bound is accessible to current and upcoming ultra-high energy neutrino experiments. Detection of a single neutrino with energy above the upper limit would exclude all sites of shock acceleration, and imply physics beyond the Standard Model. We comment on the possibility that relativistic flows launched by supermassive black hole mergers are the source of the observed ultra-high energy cosmic rays.

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The origin of ultra-high energy cosmic rays ($> 10^{18.5}$ eV; UHECRs) is unknown. Broadly speaking, they can be produced by shock acceleration via the Fermi mechanism [1–4], direct acceleration by the electromagnetic fields of compact objects [5–8], and the decays of hypothetical super-massive particles beyond the Standard Model (“top-down” scenarios) [9, 10]. Fermi acceleration is thought to operate in supernova remnants, producing the low energy CRs ($\lesssim 10^{15.5}$ eV) in the Galaxy. Similarly, the relativistic shocks of gamma-ray bursts and the flares of active galactic nuclei are leading prospective astrophysical engines for UHECR acceleration [3, 6].

Whatever their source, UHECR acceleration must occur in the local universe. If UHECRs are protons, they are attenuated on a scale of $\lesssim 100$ Mpc for energies $\gtrsim 5 \times 10^{19}$ eV by the Greisen-Zatsepin-Kuz’mín (GZK; [11]) mechanism, producing secondary particles that decay to e^\pm , γ -rays, and UHE neutrinos. If UHECRs are nuclei, photodisintegration on the cosmic infrared background suppresses the flux at a similar energy [12].

Although a decrease in the UHECR flux above the GZK threshold has now been observed [13, 14], it is unknown whether this is evidence of UHECR attenuation, or instead an intrinsic limitation to the acceleration process in astrophysical engines. If the former, then secondary UHE neutrinos with energies above the GZK cutoff should propagate to us unimpeded from across the universe [15, 16]. Since experimental searches for UHE neutrinos are sensitive up to $\sim 10^{26}$ eV [17], it is of considerable interest to understand if physical bounds can be placed on the acceleration process that limit the maximum energy of the primary UHECR spectrum.

Such a bound has been constructed for the case of direct electromagnetic acceleration [7], but no such bound has been formulated for the case of relativistic shock acceleration. Here, we show that the physics of the Fermi mechanism and synchrotron cooling, together with an absolute upper bound on the bolometric luminosity of any astrophysical engine, combine to produce an experimentally testable upper bound on the energy of the UHECR population in the universe.

The Maximum Energy of Particles.— We consider particle acceleration in a flow of total luminosity L and bulk Lorentz factor Γ . As in Ref. [3], we assume that the central engine is transient and stationary in the observer frame, and that the region of particle acceleration is a shell of radial extent $\delta r = \delta r'/\Gamma = r/\Gamma^2$, and perpendicular extent $r'_\perp = r_\perp$, where r is the distance from the shell to the engine, and where primes denote quantities in the flow rest frame. The connection between δr , r , and Γ follows from the fact that an unsteady flow of thin shell geometry traveling at $c - \delta v$, with $\delta v \ll c$, broadens kinematically to a thickness $\delta r \approx r\delta v/c$.

The comoving magnetic energy density in the shell is $u'_B = \epsilon_B L / (4\pi \Psi r^2 \Gamma^2 \beta c)$, where $\beta = v/c$ is the shock velocity, $\epsilon_B (\leq 1)$ measures the efficiency of magnetic field generation, and $\Psi (\leq 1) = \Omega/4\pi$ measures the beaming of the flow into solid angle Ω . A necessary requirement for acceleration is that [2, 3] $2\pi f R'_L < \min[\delta r', r'_\perp]$, where $R'_L = E'/(ZeB')$ is the Larmor radius, $E' = E/\Gamma = \gamma mc^2$ is the particle energy, Ze is the charge, B' is the magnetic field strength, and f is a constant of order unity. We first focus on the case with $\delta r' < r'_\perp$, and return to the physics of more highly beamed flows below. Assuming $\beta \approx 1$, which we confirm below, and combining these expressions, one obtains an upper bound on the accelerated particle energy [3]:

$$E_{\max} \lesssim \frac{Ze}{f\pi\Gamma} \left(\frac{\epsilon_B L}{2\Psi c} \right)^{1/2}. \quad (1)$$

However, there are two crucial limitations to Eq. (1). First, the same magnetic field that confines the particles to the accelerating region also causes radiative losses via synchrotron. Acceleration to E requires that the acceleration time $t'_{\text{acc}} \sim R'_L/c$ is less than the synchrotron cooling time, t'_{synch} , which sets a lower limit on Γ [3]:

$$\Gamma > \left(\frac{E}{m_p c^2} \right)^{2/5} \left(\frac{8\pi f (Ze)^3}{9m^2 c^5 \delta t} \right)^{1/5} \left(\frac{2\epsilon_B L}{\Psi c} \right)^{1/10}, \quad (2)$$

where m is the particle mass, $\delta t \sim r/(\Gamma^2 c)$ is the observed variability timescale of the system, and we have

assumed that $v'/c = 1$, where v' is the particle velocity in the rest frame of the flow. Because $t'_{\text{acc}} \propto R'_L$, the condition $t'_{\text{acc}} < t'_{\text{synch}}$ implies that radiation reaction can be ignored in deriving Eq. (2) [18].

The second fundamental constraint on Eq. (1) follows from the fact that there is a maximum L attainable by any astrophysical engine [19]:

$$L_{\text{max}} \sim c^5/G \simeq 3.63 \times 10^{59} \text{ ergs s}^{-1}, \quad (3)$$

equivalent to radiating the entire rest mass of a body in a single light travel time across its Schwarzschild radius. L_{max} is only approached during the merging of binary BHs in gravity waves. We return below to whether L_{max} in gravity waves can couple to electromagnetic fields, thus producing $u'_B \propto \epsilon_B L$ with $\epsilon_B > 0$. Here, it is sufficient to note that $L \lesssim L_{\text{max}}$ for any astrophysical engine.

The limits on Γ and L combine with Eq. (1) to produce a unique E_{max} at a critical Γ_{crit} . We find that

$$E_{\text{max}}(\delta t) = \left[\frac{9}{64\pi^6} \frac{\epsilon_B^2 m^4 c^{17} Z^2 e^2 \delta t}{\Psi^2 G^2} \right]^{1/7} \quad (4)$$

is the maximum energy of particles accelerated in relativistic shocks driven by maximally luminous astrophysical engines. To evaluate E_{max} , note that the observed variability timescale $\delta t = t/\Gamma^2$, where t is the light-travel time between the engine and the acceleration region. Since t is bounded by the time for GZK losses for protons (t_{loss}), or photodisintegration losses for nuclei,

$$E_{\text{max}}(t) \approx 1 \times 10^{24} \text{ eV} \left(\frac{A^4 \epsilon_B}{\Psi f^4} \frac{t}{t_{\text{loss}}} \right)^{1/5} \quad (5)$$

and $\Gamma_{\text{crit}} \approx 250 Z (\epsilon_B/f^{2/3}\Psi)^{3/10} (m_p/m)^{4/5} (t_{\text{loss}}/t)^{1/5}$, where $A = m/m_p$, $t_{\text{loss}} \sim 50 \text{ Myr}$ for protons or nuclei [20, 21]. For $\Gamma \neq \Gamma_{\text{crit}}$, particles are not accelerated to E_{max} . Because the classical synchrotron formula used in Eq. (2) is invalidated when the energy of the emitted photons exceeds the particle energy [22], we verified that $\gamma' B' / [m_p^2 c^3 / (\hbar Z e)] \ll 1$ for $\Gamma \geq 1$ and $t \gtrsim 10^{-4} \text{ s}$, confirming our use of the classical formula in deriving Eq. (5) for nuclei; electron cooling will be modified by QED effects, but we do not consider them here.

Protons reaching E_{max} lose energy via photomeson processes, producing secondary neutrinos. Although the maximum neutrino energy is E_{max} [20, 23], the average energy is $E_{\text{max}, \nu} \sim E_{\text{max}}/(20A)$ [23–25]; that is,

$$E_{\text{max}, \nu}(t) \sim 5 \times 10^{22} \text{ eV} \left(\frac{\epsilon_B}{\Psi f^4} \frac{1}{A} \frac{t}{t_{\text{loss}}} \right)^{1/5}, \quad (6)$$

which is maximized for protons.

Although Eq. (5) establishes an upper bound on E , astrophysical engines may not typically drive outflows with $t = t_{\text{loss}} \sim 50 \text{ Myr}$. Indeed, unsteady relativistic flows develop internal shocks, dissipating their energy on

a scale $r = \Gamma^2 c \delta t$ [26]. To evaluate Eq. (4) in this limit, we scale the variability timescale δt to the light-crossing time of the largest compact objects, super-massive BHs of $\sim 10^9 M_\odot$ ($t_L \sim 2GM/c^3 \sim 10^4 \text{ s}$):

$$E_{\text{max}}(\delta t) \sim 1 \times 10^{23} \text{ eV} \left(\frac{A^4 Z^2 \epsilon_B^2}{f^3 \Psi^2} \frac{\delta t}{10^4 \text{ s}} \right)^{1/7}, \quad (7)$$

$$E_{\text{max}, \nu}(\delta t) \sim 6 \times 10^{21} \text{ eV} \left(\frac{Z^2 \epsilon_B^2}{A^3 f^3 \Psi^2} \frac{\delta t}{10^4 \text{ s}} \right)^{1/7}, \quad (8)$$

$\Gamma_{\text{crit}} \approx 2020 Z^{5/7} A^{-4/7} (10^4 \text{ s}/\delta t)^{1/7} (\epsilon_B/\Psi)^{3/14} f^{-1/7}$. For the $10 M_\odot$ BHs that result from the collapse of some massive stars, $t_L \sim 10^{-4} \text{ s}$, and $E_{\text{max}} \sim 8.6 \times 10^{21} \text{ eV}$ for protons. Note the dependence on A and Z ; for $Z \propto A$, $E_{\text{max}}(\delta t) \propto A^{6/7}$, so that E_{max} is ≈ 30 times higher for iron nuclei than for protons.

UHE neutrinos may also come directly from the decay of unstable particles in the flow (e.g., π^\pm). Requiring $t'_{\text{acc}} < \tau\gamma'$, where τ is the particle decay time, $\tau > 8 \times 10^{-4} \text{ s} (\delta t/10^4 \text{ s})^{4/7} (\epsilon_B Z^8/A^5 f^4 \Psi)^{1/7}$ is required for acceleration. Thus, μ^\pm , π^\pm , and K^\pm may be directly accelerated, but only for $\delta t \ll 10^4 \text{ s}$, implying that it is impossible to exceed the limit of Eqs. (7) and (8) by directly accelerated unstable particles.

Extreme Beaming.— All of the above expressions are valid for the case of a beamed flow with $\delta r' < r'_\perp$. The opposite limit requires that $\Gamma \gtrsim 1/(2\Psi^{1/2})$, and for particles to be accelerated one requires $R'_L < r'_\perp$. These conditions lead to a unique E_{max} and a minimum Lorentz factor Γ_{min} above which this limit obtains:

$$E_{\text{max}}(t, \Gamma \gtrsim 1/2\Psi^{1/2}) \sim Z\alpha^{1/2} E_{\text{pl}} \sim Z 10^{27} \text{ eV}, \quad (9)$$

and $\Gamma_{\text{min}} \simeq 3 \times 10^6 (Z^5/f)^{1/2} \epsilon_B^{3/4} A^{-2} (t_{\text{loss}}/t)^{1/2}$, where E_{pl} is the Planck energy and α is the fine structure constant. Equation (9) is identical to the bound for loss-less electromagnetic acceleration [7]. We have not emphasized this case here since Γ_{min} is very high, implying a solid angle for the flow of $\lesssim 10^{-12} \text{ sr}$.

Discussion.— Our primary result is that for maximally efficient acceleration in relativistic shocks, driven by maximally luminous astrophysical engines, the maximum particle energy is given by Eq. (5). For extremely highly beamed flows (likely unphysically so), the bound is given by Eq. (9). These bounds yield maximum and average secondary neutrino energies that are within reach of current and upcoming experiments.

Figure 1 shows experimental upper bounds on the UHE neutrino intensity above 10^{19} eV from ANITA [27], WSRT[28], and FORTE [17], and projected bounds for SKA and LOFAR [29]. The Waxman-Bahcall flux is shown for reference (dashed line) [30]. The vertical solid lines show the bounds on energy derived here assuming $A = Z = f = \epsilon_B = 1$. Lines I and II show

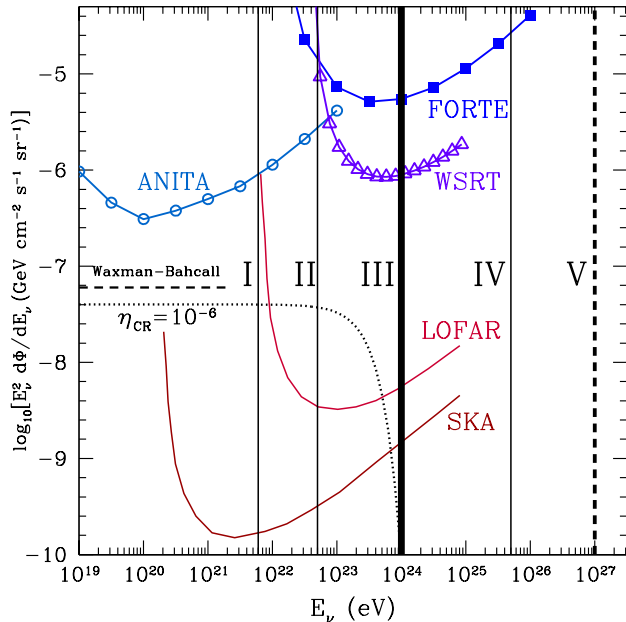


FIG. 1: Neutrino intensity versus energy. Current (ANITA, WSRT, FORTE) and projected (LOFAR, SKA) experimental upper bounds are indicated. The upper limits on accelerated particle energy derived here are indicated by the solid vertical lines I-V. Lines III and V (heavy) show the absolute upper bounds for spherical and highly-beamed flows (Eqs. 5 and 9), beyond which no particle can be accelerated by a relativistic shock launched from any astrophysical engine. Lines II and IV mark the average secondary neutrino energies expected for these two limiting cases. Line I corresponds to Eq. (8).

$E_{\max, \nu}(\delta t = 10^4 \text{ s})$ (Eq. 8) and $E_{\max, \nu}(t = t_{\text{loss}})$ (Eq. 6). The heaviest vertical solid line III marks $E_{\max}(t = t_{\text{loss}})$ (Eq. 5), the absolute upper bound on UHE neutrino energy for spherical shocks ($\Psi = 1$). For acceleration to line III, the secondary neutrino spectrum drops sharply at $E_{\max, \nu} \sim E_{\max}/20$ (line II), as does the heavy dotted curve (see below). The absolute bound for beamed flows is also shown (line V, heavy dashed; Eq. 9), as is $E_{\max, \nu}$ for such particles (line IV).

Figure 1 shows that the upper bounds presented here are testable. If the primary UHECRs that produce the yet-to-be-measured UHE neutrino flux are in fact accelerated by relativistic shocks, we predict a dramatic downturn in the UHE neutrino flux at or below $E_{\max, \nu} \simeq 5 \times 10^{22} \text{ eV}$ (line II; Eq. 6), and most likely well below $\sim 10^{22} \text{ eV}$, since our supposition is that actual astrophysical engines fail to reach L_{\max} , have $\epsilon_B \ll 1$, and may not have $\Gamma = \Gamma_{\text{crit}}$, or $t = t_{\text{loss}}$ (Eq. 5). In turn, the observation of a cutoff in the UHE neutrino spectrum will put limits on the sources' overall power, since L is directly connected with E_{\max} [3]. In particular, we can invert the expressions above to provide a lower limit on the sources' luminosity, given the observation of a single

UHECR of energy $E_{21} = E/10^{21} \text{ eV}$:

$$L \gtrsim 2 \times 10^{54} \text{ ergs s}^{-1} E_{21}^{7/2} \frac{\Psi}{Z A^2 \epsilon_B} \left(\frac{1 \text{ s}}{\delta t} \right)^{1/2}. \quad (10)$$

Importantly, the observation of a single neutrino above E_{\max} (line III) immediately rules out spherical shock acceleration as the origin of the primary particle's high energy. Indeed, since even for a mono-energetic primary proton spectrum at E_{\max} (III), the vast majority of the secondary neutrinos will have $E_{\max, \nu}$ (II), the detection of neutrinos above $E_{\max, \nu}$ strongly indicates that the primary was not accelerated by a relativistic shock. The remaining possibilities are that (1) the flow was exceedingly highly beamed ($\Omega < 10^{-12} \text{ sr}$), (2) QED effects suppressed synchrotron cooling (requiring $t < 10^{-4} \text{ s}$ at $L = L_{\max}$), (3) the primary particle was produced by an unknown class of near-maximal loss-less electromagnetic accelerators, as in [7], or (4) the detected neutrino was generated by the decay of a super-massive primary from beyond the Standard Model [9, 10].

BH-BH Mergers as UHECR Sources?— The fact that L_{\max} (Eq. 3) is only thought to be approached in gravity waves during BH-BH mergers motivates a consideration of these events as the primary source of the UHECRs.

If we assume that the galaxy merger rate at $z = 0$ ($\sim 0.03 \text{ Gyr}^{-1}$ per galaxy; [31]) corresponds to the merger rate of $M_{\text{BH}} \sim 10^8 M_{\odot}$ BHs, that $\eta_{\text{CR}} M_{\text{BH}} c^2$ is radiated in UHECRs per merger, and that the local number density of large galaxies like the Milky Way is 10^{-2} Mpc^{-3} , by comparing the volumetric power produced in CRs with the inferred UHECR production rate per comoving volume ($\approx 0.7 \times 10^{44} \text{ ergs yr}^{-1} \text{ Mpc}^{-3}$; [30]) one finds that $\eta_{\text{CR}} \sim 10^{-6}$ is required if such mergers are to dominate UHECR production. Assuming an E^{-2} UHECR spectrum to $E_{\max}(t = t_{\text{loss}})$, in Figure 1 we sketch the expected neutrino spectrum (*dotted curve*). Taking the local GZK volume to be $\sim (100 \text{ Mpc})^3$, the local merger rate is of order 0.3 Myr^{-1} , implying that ~ 100 BH-BH merger events would contribute to the observed UHECRs. Although such particles would be expected to trace the large-scale distribution of galaxies on the sky, as has been claimed by Auger [32], the low source density and high energy release per event may be ruled out if the UHECRs are protons [33] (see Ref. [34]).

Stellar-mass BH-BH mergers might also contribute to the UHECR budget, but given the inferred rate per galaxy ($\sim 10^{-8} - 10^{-6} \text{ yr}^{-1}$ [35]) the UHECR energy production rate per volume is smaller than for supermassive BH-BH mergers by $\sim 10^3 - 10^5$. Nevertheless, since these sources are transient and potentially nearby, they could in principle contribute to the observed UHECR budget.

Can BH-BH mergers accelerate CRs? Simulations have argued that the efficiency of production of electromagnetic waves in the vicinity of BH-BH mergers may be large, but only for ambient magnetic field strengths far

in excess of those thought to accompany accretion [36]. Thus, ϵ_B in our expressions is the primary unknown in forwarding BH-BH mergers as the source of UHECRs.

Consequences of Maximal Shocks.— If any astrophysical engine, be it merging BHs or otherwise, reaches L_{\max} , with $\Gamma = \Gamma_{\text{crit}}$, there are observational consequences beyond the direct detection of UHECRs or neutrinos. In particular, the particles will produce synchrotron radiation with observed photon energy $E_{\text{synch}} = \Gamma h(3/4\pi)\gamma'^2(ZeB'/mc) \sim 20(10^4 \text{ s}/\delta t)^{1/7} \text{ TeV}$. The power radiated per particle is $\sim E/2\pi\Gamma^2\delta t$.

Again considering BH-BH mergers and spherical shocks, the total received synchrotron power is $L_{\text{synch}} \sim \eta_{\text{CR}} M_{\text{BH}} c^2 / (2\pi\delta t) \sim 3 \times 10^{51} (10^4 \text{ s}/\delta t) (\eta_{\text{CR}}/10^{-6}) \text{ ergs s}^{-1}$ for $M_{\text{BH}} = 10^8 M_{\odot}$. If the particles have an E^{-2} spectrum extending to $E_{\max}(\delta t = 10^4 \text{ s})$, $\nu L_{\nu}^{\text{synch}} \sim L_{\text{synch}} / (2 \ln(E_{\max}/mc^2)) \sim 5 \times 10^{49} \text{ ergs s}^{-1}$ at E_{synch} with $\nu L_{\nu} \propto \nu^{1/2}$ for $E < E_{\text{synch}}$. The observable rate of such events would be $\sim 10 \text{ yr}^{-1}$, and the flux would be $\sim 5 \times 10^{-8} \text{ GeV s}^{-1} \text{ cm}^{-2}$ at a luminosity distance of $\sim 7 \text{ Gpc}$. Such an event could have the appearance of a long-duration gamma-ray burst (GRB), and would be observable by the *Fermi* and *Swift* satellites. Whether or not a sub-class of long-duration GRBs might be ascribed to such a mechanism is unknown, but unlikely. Similar statements could be made for the analogous events from lower mass BH-BH mergers, and the association with short-duration GRBs. More likely, the lack of such events may limit η_{CR} to be $\ll 10^{-6}$, ϵ_B to be $\ll 1$, or $\Gamma \neq \Gamma_{\text{crit}}$ in BH-BH mergers.

Conclusion.— We have derived robust, experimentally testable upper limits to the energies of primary UHECRs accelerated by relativistic shocks driven by astrophysical engines. For such an engine to accelerate particles to $E_{\max} \sim 10^{24} \text{ eV}$ (Eq. 5) it must have $L = L_{\max}$, and the relativistic outflow it drives must reach $\Gamma = \Gamma_{\text{crit}}$, with $\epsilon_B = 1$. For highly beamed flows, $E_{\max} \sim 10^{27} \text{ eV}$ (Eq. 9), with the additional requirement that the solid angle for the flow must be $\lesssim 10^{-12} \text{ sr}$, likely unattainable in real astrophysical engines. If any of these conditions is not met, E_{\max} is not reached. Particles reaching E_{\max} suffer photomeson or photodisintegration losses, producing secondary neutrinos with average energy ~ 20 times lower than E_{\max} for protons, observable from across the universe. Thus, if a single UHE neutrino is detected above E_{\max} it will strongly imply the existence of an unknown class of loss-less maximal electromagnetic accelerators [7], or physics beyond the Standard Model.

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